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Modernizing reference frames

– the foundation of geodesy

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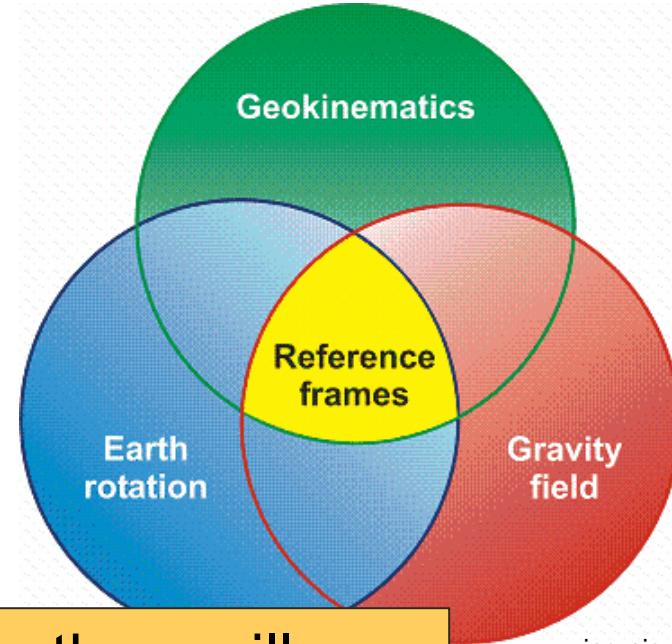


Geodesy?

Geodesy to measure:

- Geometry of the Earth
- Earth's orientation in space
- Earth's gravity field

... and changes therein!

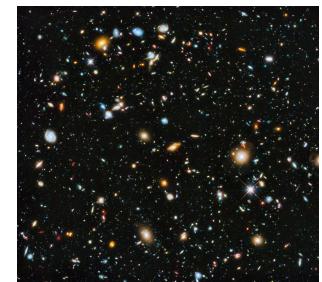
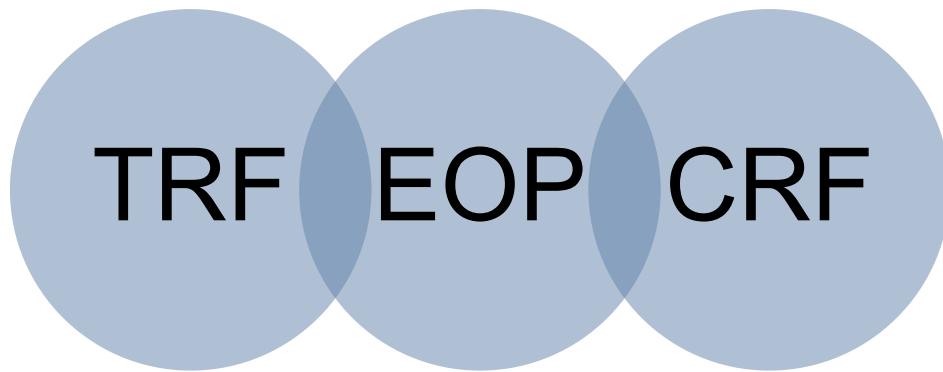


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Reference frames connect the three pillars

Reference frames?

- Reference frames are realizations of coordinate systems
 - On Earth: terrestrial reference frames (TRF)
 - In Space: celestial reference frames (CRF)
- Connection (rotation) between TRF and CRF:
 - Earth orientation parameters (EOP)



Reference frames. Why?

- Sea level monitoring
 - Navigation tasks
 - Satellite operations
 - Geodynamics
 - ...
- benefits to science & society



Reference frames need to be highly accurate

Reference frames. How?

Space geodetic techniques:

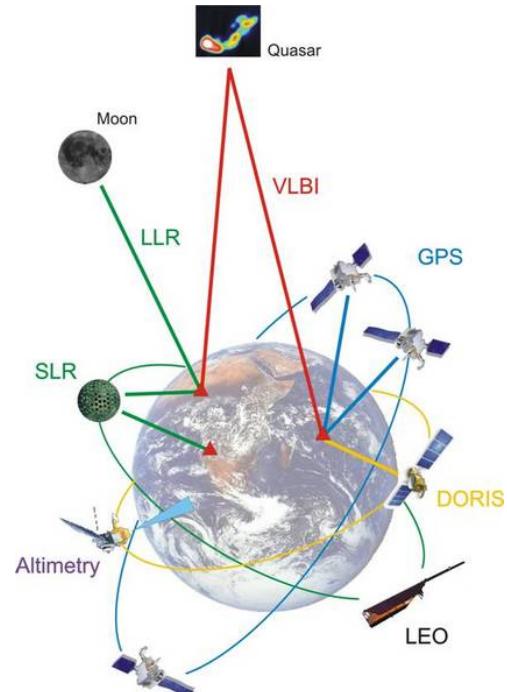
- GNSS, VLBI, SLR, DORIS, gravity missions, altimetry,...



...

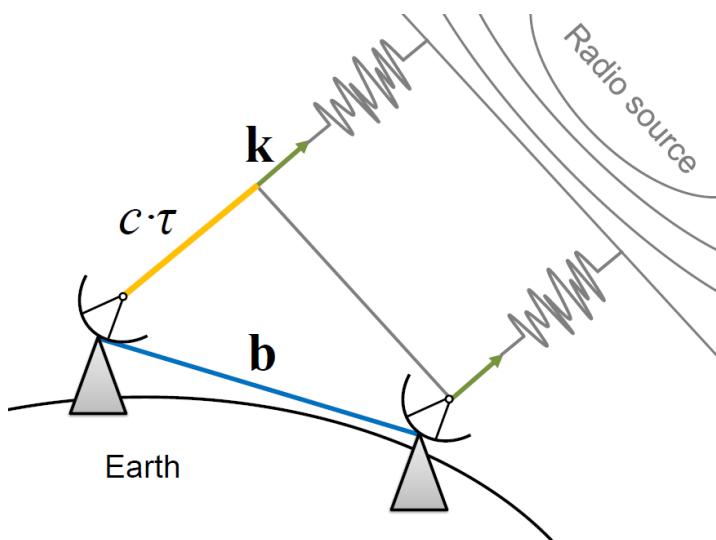
Individual strengths and weaknesses

Combination of techniques for best results



Very long baseline interferometry

- One of the primary space-geodetic techniques
 - Unique: full set of Earth orientation parameters celestial reference frame
 - Important for TRF scale



Observation principle

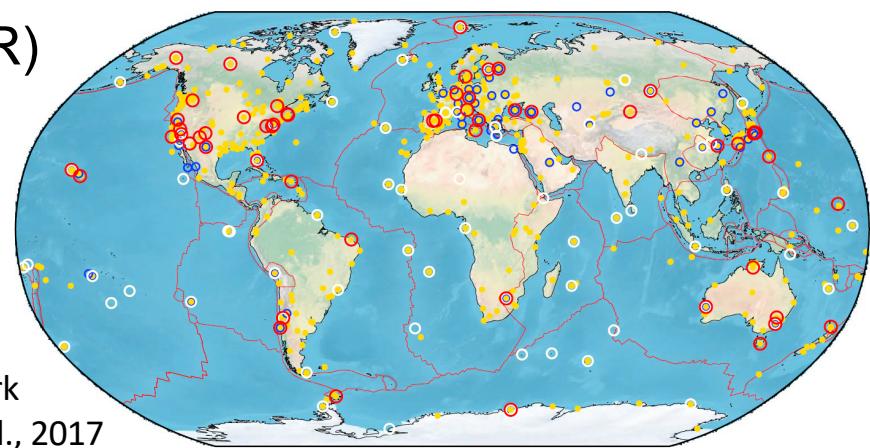
Measurement of difference of arrival time of radio signals from extragalactic radio sources at two or more observing stations

TRF – definition and realization

- Reference “system” - definition
 - Origin: geocenter
 - Scale: SI meter, consistent with Geocentric Coordinate Time (TCG)
 - Orientation: BIH orientation 1984.0
- Reference “frame” - realization: 3D station positions
 - Origin: SLR
 - Scale: SLR & VLBI
 - Orientation: no-net-rotation (NNR)
 - Densification: GNSS

IERS Conventions, 2010

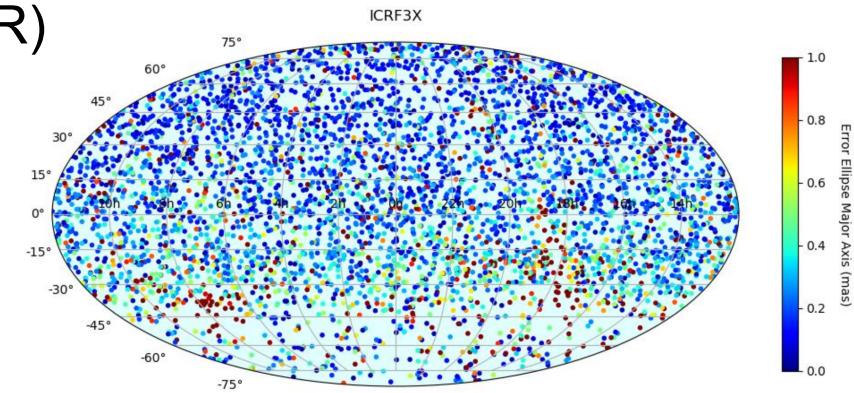
JTRF2014 network
Abbondanza et al., 2017



CRF – definition and realization

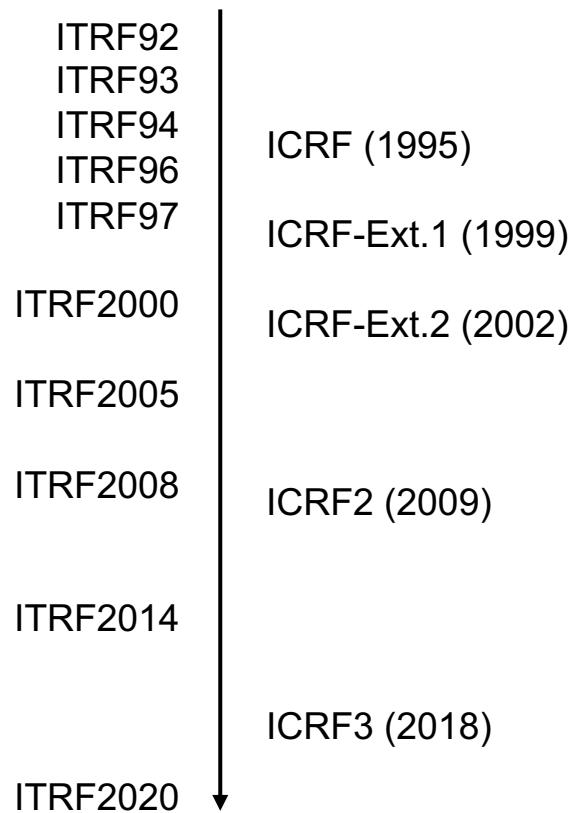
- Reference “system” - definition
 - Origin: barycenter of the solar system
 - Scale: consistent with Barycentric Coordinate Time (TCB)
 - Orientation: FK5 / J2000 equator
- Reference “frame” - realization: 2D radio source positions
 - VLBI only
 - Orientation / scale: through relativistic modeling
 - Orientation: no-net-rotation (NNR)

ICRF3 radio sources
Charlot et al., 2018



International TRF/CRF

- Official products of the IERS
 - International Earth Rotation and Reference Systems Service



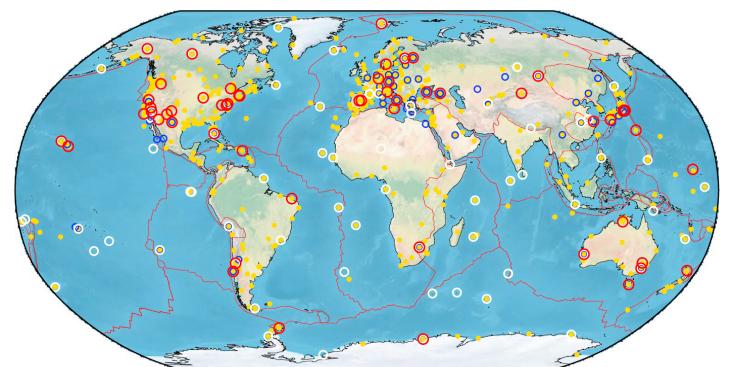
ITRF solutions

- Combination of four space-geodetic techniques
 - GNSS, VLBI, SLR, DORIS
- ITRF2008 and earlier: linear coordinate model
 - Coordinate offset + velocity
- ITRF2014 (Altamimi et al., 2016)
 - Linear + post-seismic deformations (+ annual/semi-annual)
- DTRF2014 (Seitz et al., 2016)
 - Linear + loading displacements model
- JTRF2014 (Abbondanza et al., 2017)
 - Time series + linear + annual/semi-annual



JTRF2014 – ITRF candidate solution by JPL

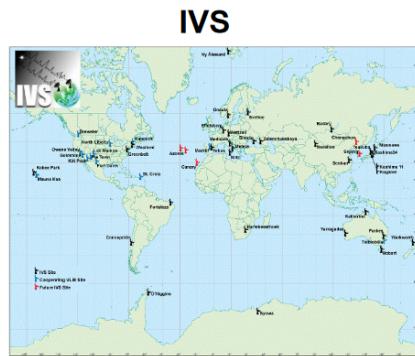
- Time series TRF based on ~1000 stations with weekly resolution
- Considers irregular station behavior
- Very good agreement of center-of-mass variations with geophysical estimates (Wu et al., 2015)
- Better performance than ITRF2014 when applied in precise orbit determination (Zelensky et al., 2018)



JTRF2014 network
Abbondanza et al., 2017

ICRF solutions

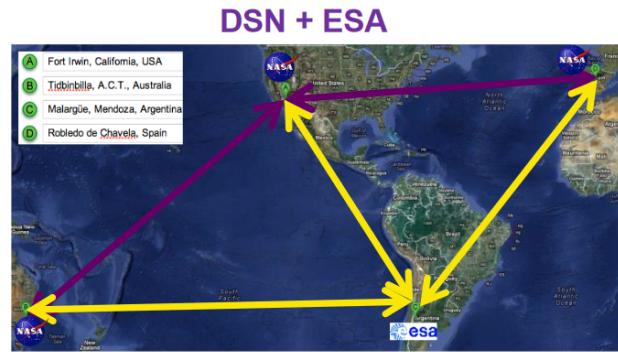
- Only based on VLBI data
- Assumption that radio source coordinates are constant
- ICRF2 and earlier: S/X band observations
- ICRF3: three-frequency frame



S/X band



VLBA



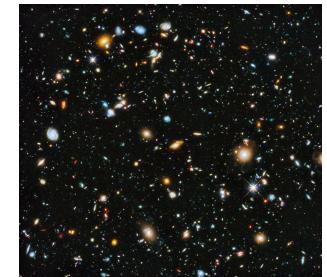
X/Ka band

Charlot et al., 2018

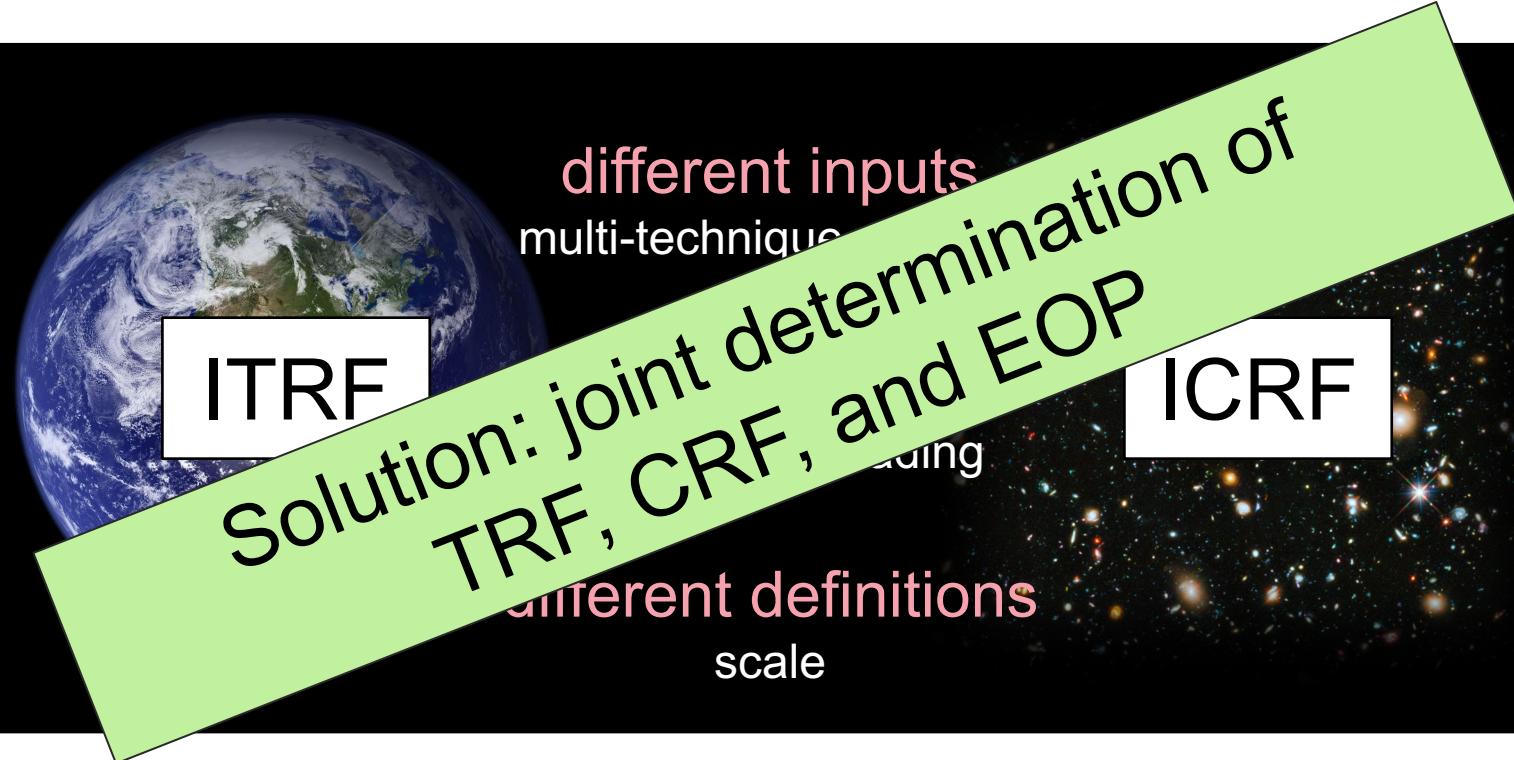
- Future: impact of Gaia

Issues of current ITRF and ICRF solutions

- ITRF
 - Aging frames (only updated every 6 years)
 - Non-linearities insufficiently addressed
 - Issues of individual techniques
- ICRF
 - No combination
 - Weakness in the South
 - Radio source structure not considered
- ITRF and ICRF are not consistent with each other



Inconsistencies between TRF and CRF



EOP are not the same for ITRF and ICRF

Modernizing reference frames

This talk: my efforts to address current issues

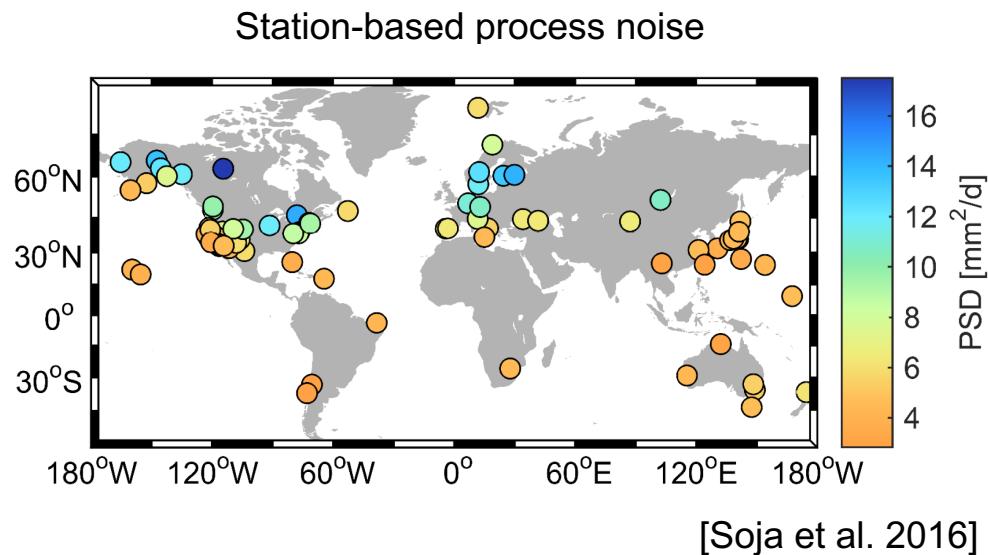
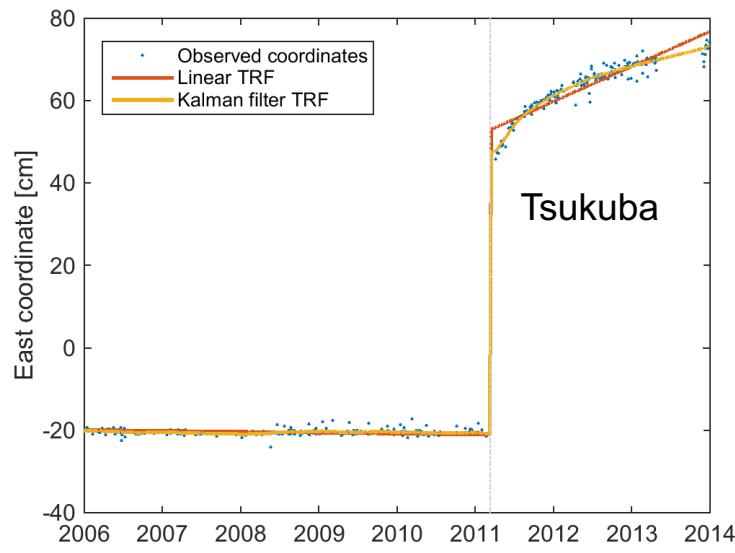
1. TRF determination
2. CRF determination
3. Joint determination

TRF determination



Kalman filter TRF approach

- TRF defined by coordinate time series
- Coordinate changes treated as stochastic processes
- Process noise based on geophysical processes
 - Loading displacements due to atmosphere, oceans, hydrology

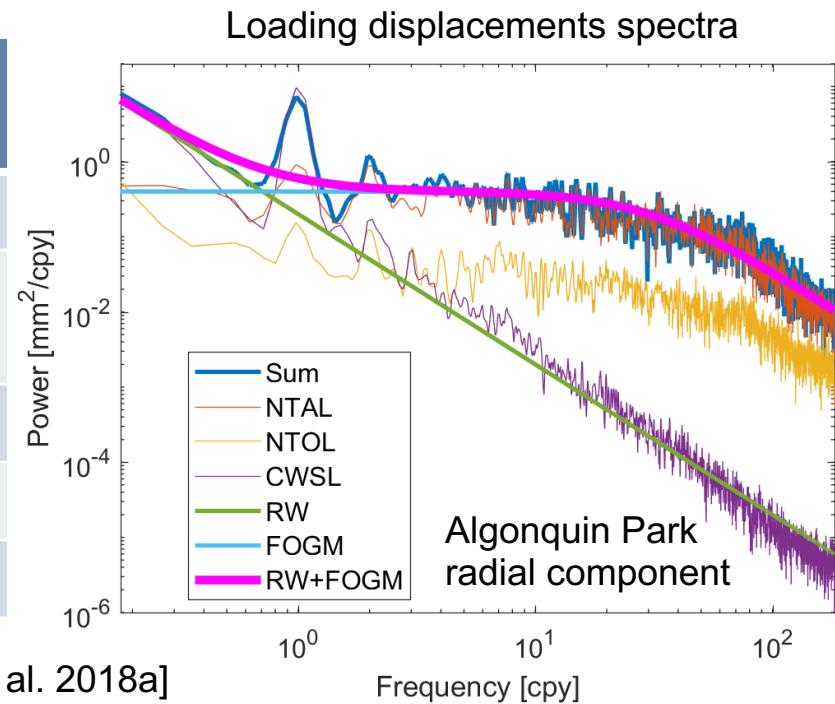


Effect of process noise on coordinates

- Selection of stochastic process and amount of process noise critical for TRF performance
 - Precision of coordinates and ability to predict future coordinates

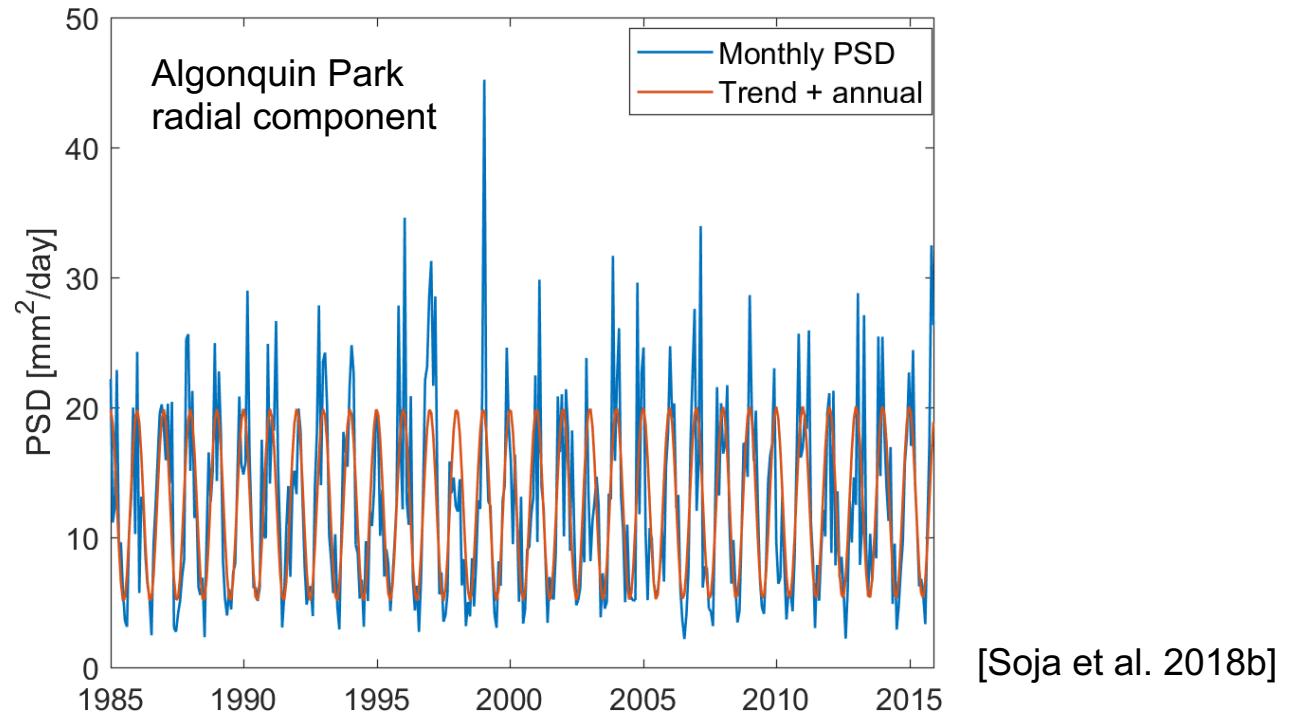
3-D WRMS [mm]	Coordinate precision	Predicted coordinates
Zero noise	14.0	15.1
Random walk	7.4	17.8
Scaled RW	10.2	15.8
White noise	11.4	15.1
AR(1)	10.7	15.0

[Soja et al. 2018a]

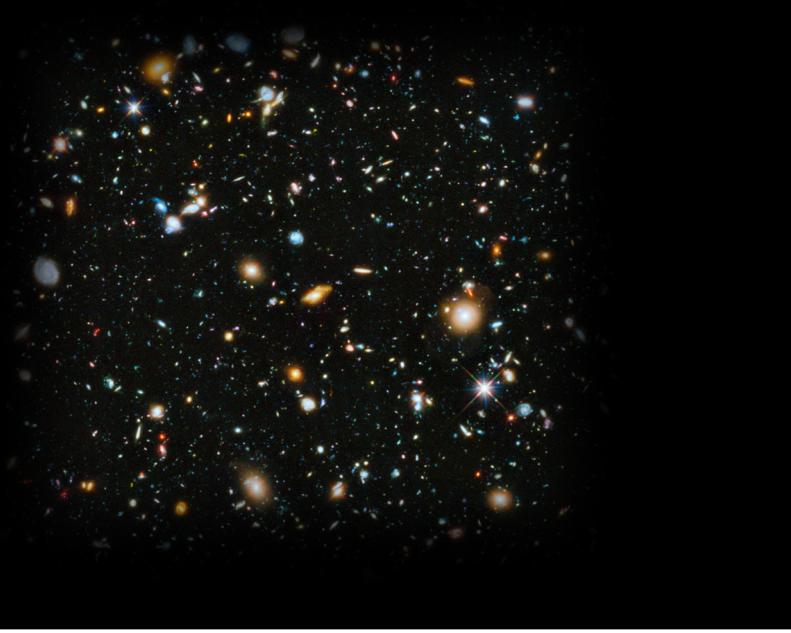


Time-dependent process noise

- Monthly determination of process noise values
- TRF coordinates differ by **up to 1 cm** between solutions with monthly and constant process noise models

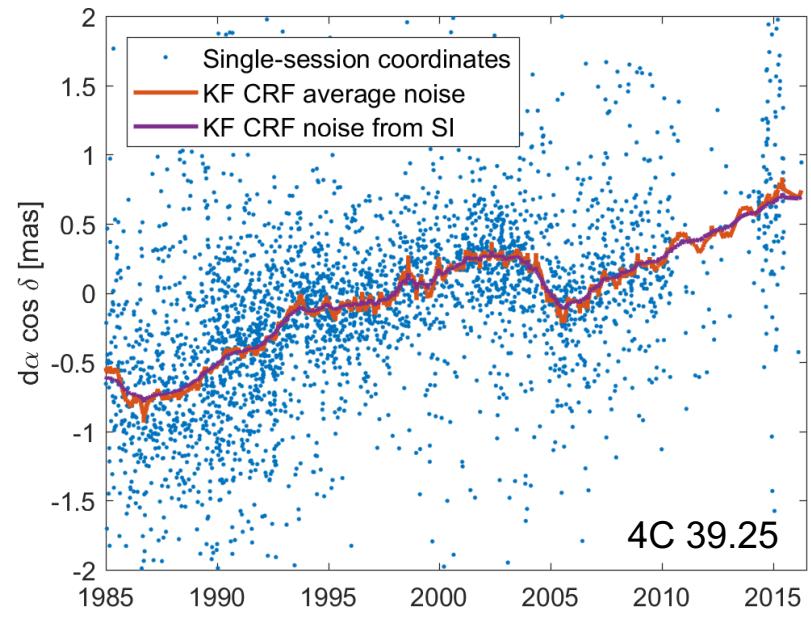
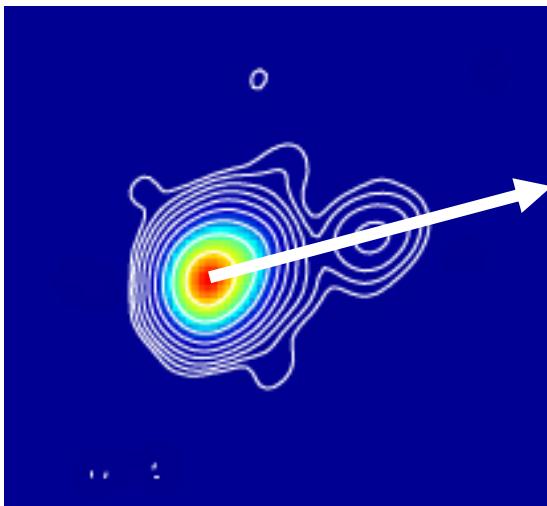


CRF determination



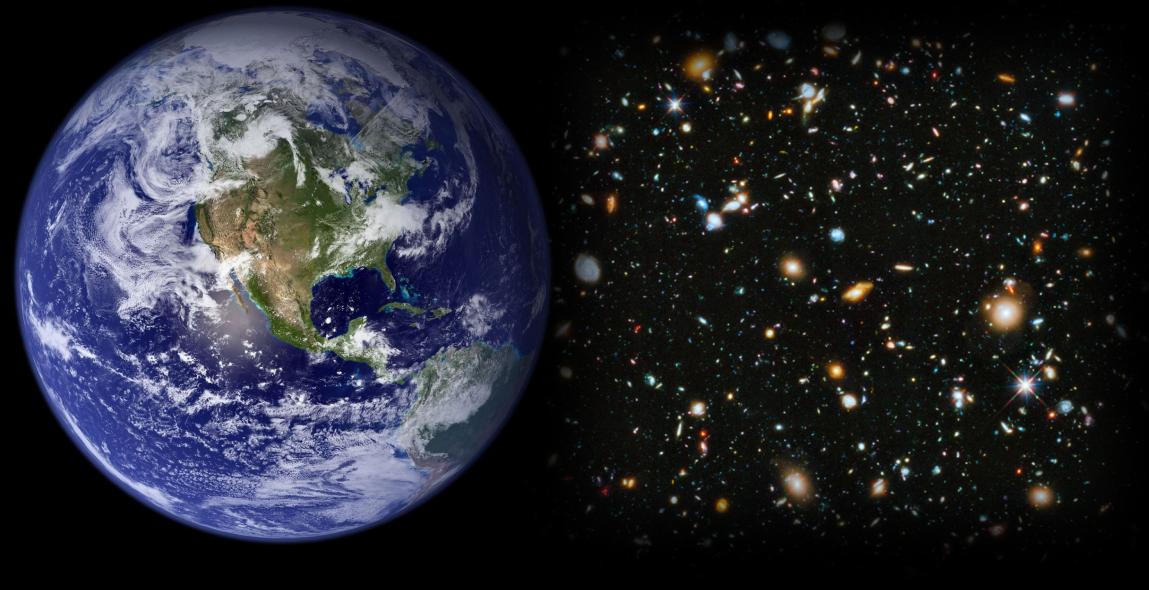
Kalman filter CRF approach

- Coordinates of radio sources subject to variations due to changes in source structure
- Process noise based on physical properties of radio sources, derived from radio source images
 - Jet direction, structure index

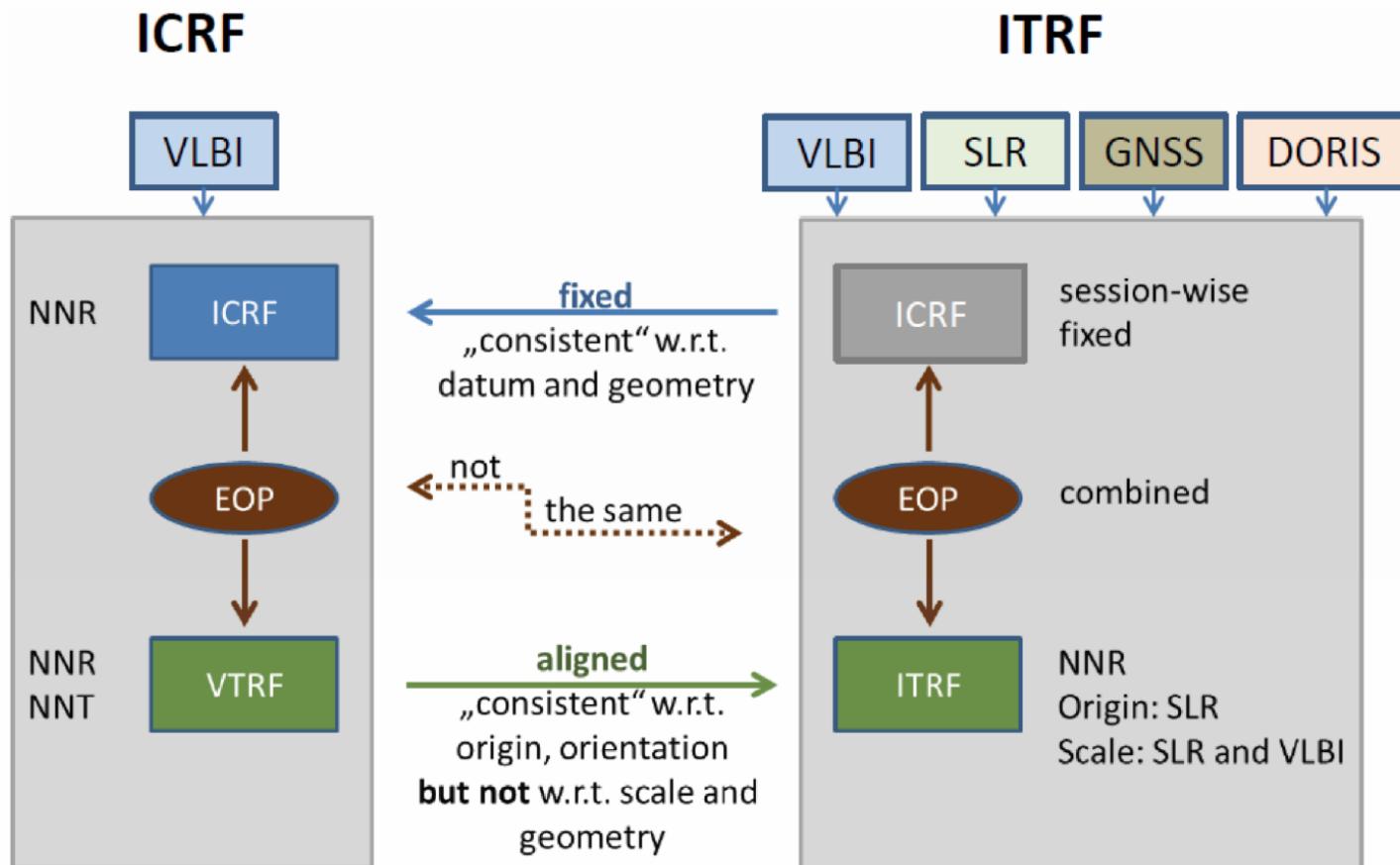


[Soja et al. 2017], [Soja et al. in prep.]

Joint TRF and CRF determination

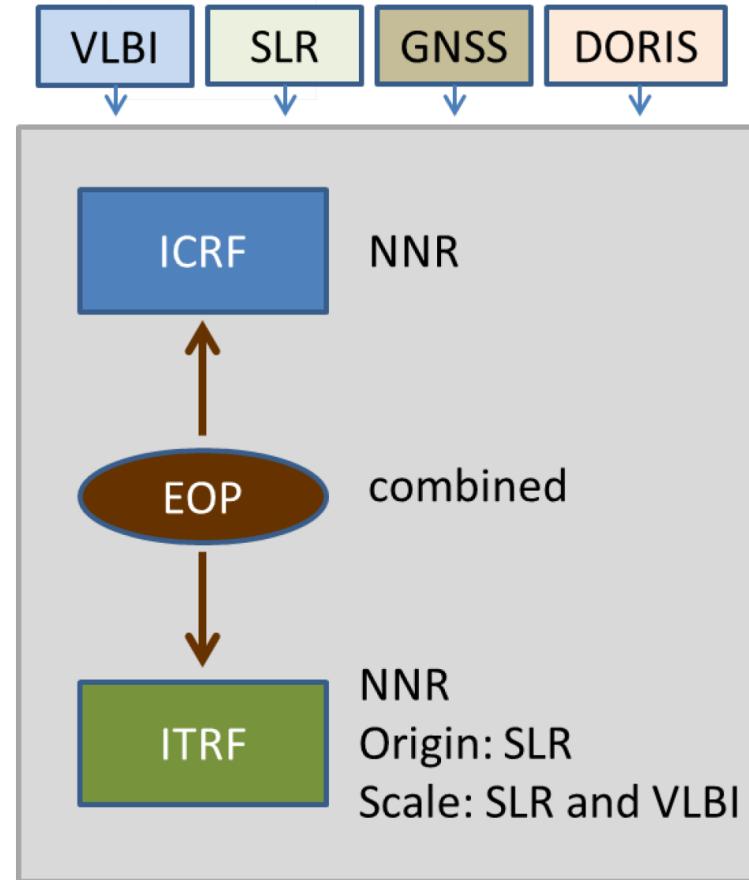


Inconsistent determination of ITRF and ICRF



[Seitz et al. 2012]

Consistent determination of ITRF and ICRF



[Seitz et al. 2012]

Methodology

- Connection between TRF and CRF:
EOP related to terrestrial (R_{xyz}) and celestial (A_{123}) rotations

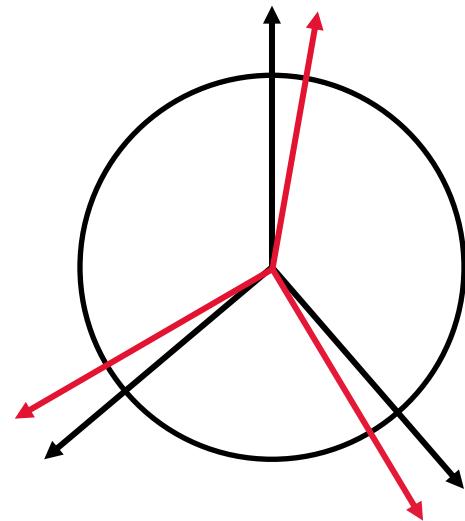
$$x_{p,t}^{obs} = x_{p,t}^{est} + R_{y,t}$$

$$y_{p,t}^{obs} = y_{p,t}^{est} + R_{x,t}$$

$$UT_t^{obs} = UT_t^{est} - R_{z,t} \cdot r' + A_{3,t} \cdot r'$$

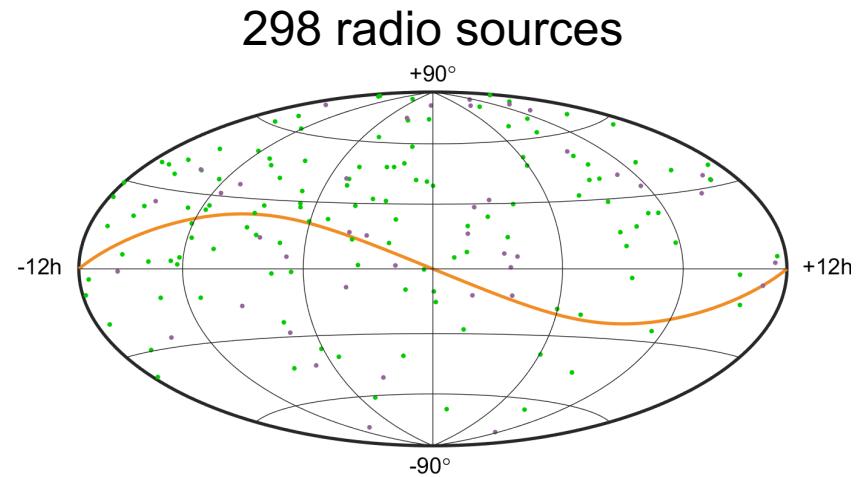
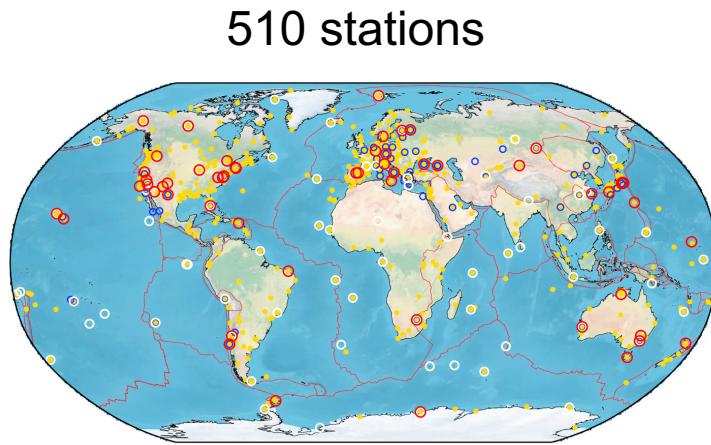
$$dX_t^{obs} = dX_t^{est} + A_{2,t}$$

$$dY_t^{obs} = dY_t^{est} + A_{1,t}$$



Input data

- JTRF2014 (Abbondanza et al. 2014) reduced network for GNSS, SLR, and DORIS
- GSFC operational solution (*gsf2016a*) for VLBI
- Time span 1992.0 – 2015.0



Results – transformations

- Helmert transformation w.r.t. ITRF2014

[mm]	Tx	Ty	Tz	λ	Rx	Ry	Rz
VLBI offset	-0.77	0.70	-1.65	2.81	0.31	0.05	0.26
VLBI rate [/yr]	-0.02	0.05	-0.09	0.13	-0.06	-0.02	-0.09
Comb offset	-0.91	-0.52	-0.12	2.53	3.12	0.54	1.78
Comb rate [/yr]	-0.01	-0.22	0.37	-0.47	0.13	-0.33	-0.03

- Celestial rotations w.r.t. ICRF3

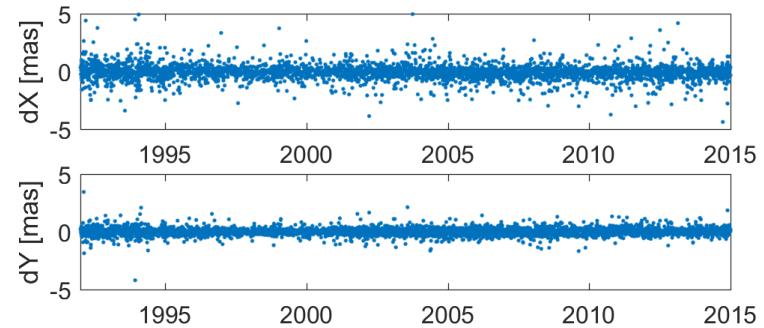
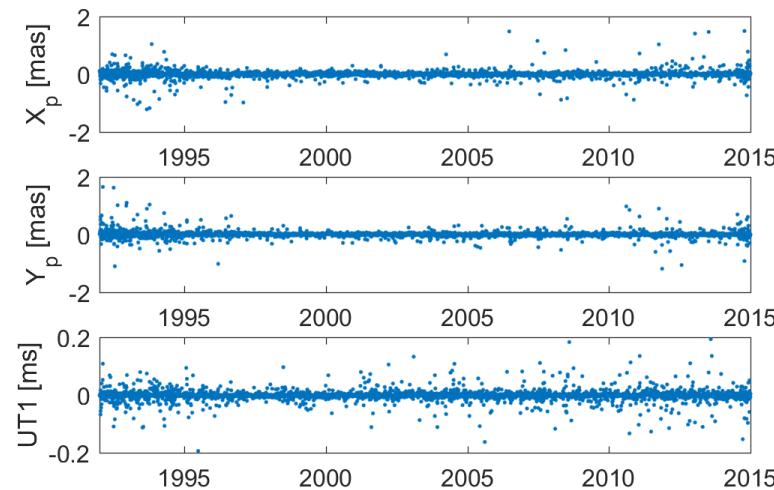
[mas]	A1	A2	A3
VLBI	0.218	-0.087	0.107
Comb	-0.042	-0.211	0.001

Coordinates
averaged over
whole time span

EOP comparisons

- Difference w.r.t. IERS C04 14

RMS [mas]	x_p	y_p	UT1 [ms]	dX	dY
VLBI	0.27	0.24	0.061	1.23	0.88
Comb	0.21	0.16	0.048	1.23	0.88

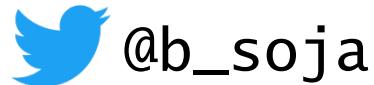


Conclusions

- TRF and CRF important for geodesy, science, and society
- ***Modernizing reference frames:***
- Improvements of TRF and CRF solutions by sophisticated **stochastic modeling** of coordinate variations
- Consistency of **TRF, CRF, and EOP** by joint determination

Thanks for your attention!

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